

## **Final Report**

**Title:** A New Eddy-Based Model for Wall-Bounded Turbulent Flows

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## 1. Abstract

Fundamental studies of wall-bounded turbulent flows were conducted with the aim of developing models that capture its correct spectral behavior and that allow prediction of Reynolds stress distributions in wall-bounded flows across a large range of Reynolds numbers. The model accounts for the recent new findings in wall turbulence concerning large-scale motions and the interaction with the wall and drag producing mechanisms. The experimental results shed light on the important differences between pipe, channel and boundary layer flows, which to date have been regarded as equivalent. The model forms the basis of a new approach to the near-wall model problem in LES (large-eddy simulation), and preliminary results show it to work effectively as a correction scheme for spatial resolution effects in hot-wire anemometry measurements in wall-turbulence. The research has been a collaboration between the University of Melbourne (PI Marusic) and Princeton University (PI Smits).

## 2. Objectives

The aim of the research was to investigate and develop a new model that captures the correct spectral behavior of wall-bounded turbulence, allowing prediction of Reynolds stress distributions in wall-bounded flows. Over the one-year funding period this involved a number of tasks, which included:

### Task 1

Carry out hot-wire anemometry experiments covering a large Reynolds number range. This involves the use of the High Reynolds Number Boundary Layer Wind Tunnel (HRNBLWT) at the University of Melbourne and other facilities.

### Task 2

Measure turbulence profiles in three facilities for matched Reynolds numbers.

Turbulence profiles will be measured for fixed Reynolds number in three separate facilities: the HRNBLWT, a pipe flow facility and a channel flow facility. This will allow a comparison to be made of the differences between these three canonical wall-bounded flows, thus verifying whether the previously documented very-large-scale-motions (VLSM) and superstructures are different in these three wall-bounded turbulent flows. The profile measurements will have the same procedure as Task 1 but in the different facilities.

### Task 3

Analyze data taken in the atmospheric surface layer by the PI's group previously at the SLTEST site on the salt-flats of Western Utah.

The main dataset is from experiments conducted in May 2005 involving 18 sonic anemometers that are simultaneously sampled.

### Task 4

Use all of the above experimental data in conjunction with the Princeton group to test and refine the model of wall-turbulence over the large Reynolds number range covered by the

experiments. This will involve refining our preliminary formulations for the spectral turbulence signatures. This work will be done using Matlab code.

### Task 5

Write-up the results of the research in journal and conference papers.

## **3. Introduction**

Predicting and understanding wall-bounded turbulent flows as a function of Reynolds remains a significant challenge. This is of great practical relevance as such flows are present in all high Reynolds number aerospace applications.

The modelling work proposed here is similar in concept to the attached eddy model originally proposed for the logarithmic region of wall-bounded flows by Perry, Henbest & Chong (1986). Scaling arguments were advanced for particular regions of the spectrum, where low wavenumber motions were assumed to scale on outer layer variables ( $u_\tau$  and  $\delta$ ), intermediate wavenumbers were assumed to be related to attached eddies (in the sense of Townsend) so that they scaled inversely with the distance from the wall ( $y^{-1}$ ), and high wavenumbers were assumed to follow Kolmogorov scaling ( $\eta$  and  $\nu$ ). Overlap arguments then defined (for the logarithmic part of the velocity profile) a region of  $k^{-1}$  and  $k^{-5/3}$  in the spectrum for the streamwise component. By integrating the spectrum, scaling laws were derived for smooth and rough walls (Perry & Li, 1990). By using largely empirical input, the model was extended to cover the complete outer layer (by Marusic, Uddin & Perry, 1997), and to include the near-wall region (by Marusic & Kunkel, 2003). The success of this hybrid model is clear from the results shown in Figure 1.

Despite its success, there are a number of compelling reasons to revisit this model. First, the model is based on the presence of  $k^{-1}$  and  $k^{-5/3}$  regions in the spectrum. Although the  $k^{-5/3}$  is well established, experiments now indicate that the  $k^{-1}$  region is only evident at very high Reynolds numbers over a very limited spatial extent. Second, the interactions between outer layer motions and inner layer motions has become much clearer in recent years, and the simple division between inner and outer layer scaling that leads to the  $k^{-1}$  region fails to capture that interaction. Specifically, the region where we might expect  $k^{-1}$  scaling corresponds to the wavenumbers occupied by the LSMs, and experiments have clearly shown that although the LSMs appear to behave as attached motions, they do not scale simply as  $y^{-1}$ . Third, the importance of the VLSMs was not appreciated until recently. For example, the low wavenumber VLSMs contribute about half of the total energy content of the streamwise turbulence component. Also, they do not scale with outer layer variables as assumed in the Perry *et al.* model. Fourth, it has become clear that the relative importance of LSMs, VLSMs, and superstructures depends on the nature of the flow: they behave differently in pipes, channels and boundary layers (Monty *et al.* 2007, Bailey, Hultmark & Smits 2008), something that is not captured in the original model. Fifth, the original model does not include the effects of pressure gradient (although some steps were taken by Perry, Marusic & Jones 2002), compressibility (although steps were taken by Fernando & Smits 1988, and Dussauge & Smits 1997), or heat transfer.

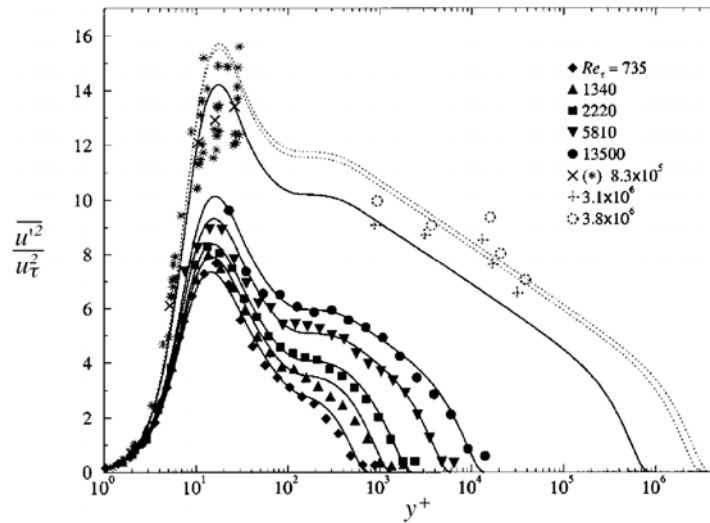


Figure 1: Streamwise turbulence intensity measurements: high Reynolds numbers from ASL (Metzger & Klewicki; Marusic et al.); low Reynolds number data from DeGraaff & Eaton (2000). Lines are model results from Marusic & Kunkel (2003).

#### 4. Theory/Analysis/Experiment

To overcome the limitations of the existing model described above, the approach adopted combines theoretical and experimental study to develop a new model that captures the correct spectral behavior of wall-bounded turbulence, that will potentially allow prediction of Reynolds stress distributions in wall-bounded flows with pressure gradients, compressibility and heat transfer.

The experiments at the University of Melbourne were carried out in the Walter Bassett Aerodynamics Laboratory. The laboratory is fully equipped with multiple channel hot-wire anemometry and other required instrumentation, and use was made of three wind tunnel facilities. The first is the HRNBLWT (High Reynolds Number Boundary Layer Wind Tunnel). This is a unique facility in terms of the quality of the flow (low freestream turbulence intensity) and the Reynolds number that can be achieved (up to  $R_q=70,000$ ). The long, 28 m, working section of the HRNBLWT produces thick boundary layers of order 350 mm, which ensures excellent spatial resolution. The other two facilities include a pipe-flow apparatus with 450-diameter length, ensuring fully developed flow, and a channel-flow facility with half-channel height of 50 mm. The three facilities are described respectively in Hutchins & Marusic (2007), Perry *et al.* (1986) and Monty *et al.* (2007).

Below are photographs of the HRNBLWT.



HRNBLWT - University of Melbourne

## 5. Results and Discussion

Experiments were carried out as planned and this allowed us to compare the three canonical wall-bounded flows, that is pipe, channel and flat-plate turbulent boundary layer flows, at a matched Reynolds number and with matched measurement and spatial resolution conditions. This had never been done before. From this we were able to directly compare spectra between these flows as shown in Figure 2.

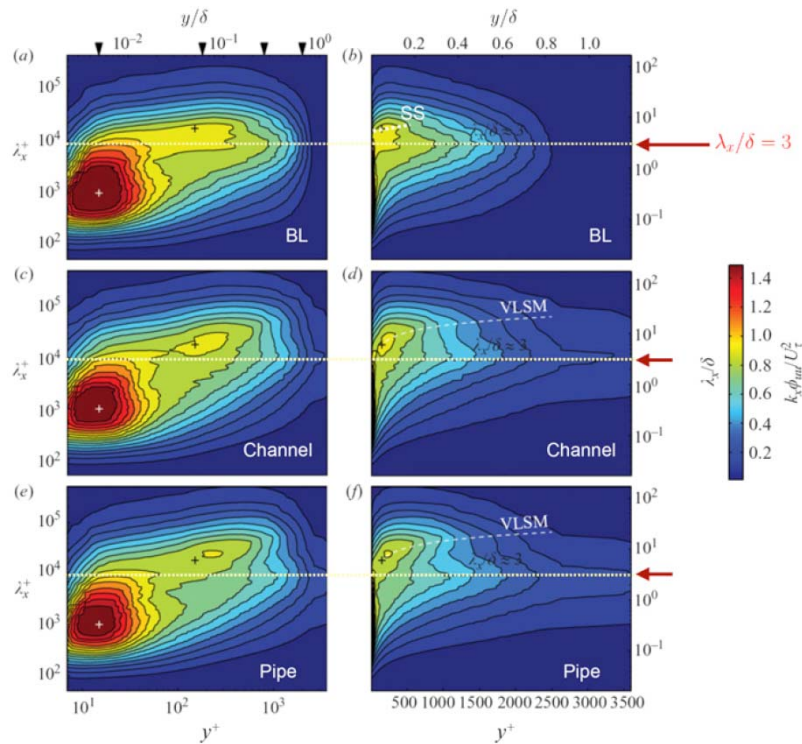


Figure 2: Maps of premultiplied  $u$  spectra as a function of streamwise wavelength  $\lambda_x$  and distance from the wall. Figures show (from top to bottom) turbulent boundary layer (a, b), channel (c, d) and pipe (e, f), respectively. Right-hand figures have a linear abscissa, to emphasize the differences in the outer region between VSLM in pipes and channel and the superstructures in boundary layers. Red arrows indicate the wavelength  $\lambda_x / \delta = 3$ .

Figure 2 indicates that the largest energetic scales in pipe and channels are distinctly different to those found in a boundary layer. Although the large-scale phenomena have

been shown to be qualitatively similar (Hutchins & Marusic 2007a; Monty *et al.* 2007), their contributions to the energy continues to move to longer wavelengths with distance from the wall in internal flows. The opposite occurs in boundary layers, where outer-flow structures shorten very rapidly beyond the log region. That is, VLSMs in internal flows are likely different from superstructures in boundary layers; qualitatively the structures are similar, however, the VLSM energy in internal flows resides in larger wavelengths and at greater distances from the wall than superstructures in boundary layers. Interestingly, for  $y/\delta < 0.5$  the different energy distributions in pipes and channels and ZPG boundary layers occur in regions where the streamwise turbulence intensity is equal. The results suggest that all three flows might be of a similar type structure, with energy simply redistributed from shorter to longer scales for the pipe and channel flow cases. Whether the quantitative differences are due to the interaction of the opposite wall in internal flows, or to the intermittency of the outer region in boundary layers, remains uncertain.

The differences found in pipes, channels and boundary layers indicate that some care is needed when comparing statistics from one of these flows to another (and this is not commonly done in the literature).

In order to model the spectra an attempt was made using the three eddy motions modeled using Gaussian distributions in the log of the wave number. The distributions resemble closely the spectral content of wavelets in physical space, specifically the Mexican Hat wavelet that mirrors the “simple” or “schematic” eddy proposed by Tennekes & Lumley (1972). The energy contained at each wavenumber is taken to be a simple sum over all eddy types, neglecting nonlinear interactions among eddies. The high wavenumber part of the spectrum is bounded by the  $k^{-5/3}$  inertial and dissipation ranges, which are modeled as a single cutoff using a modified Pao spectrum. The results are compared with the data of Hutchins & Marusic (2007b) in Figure 3, which show the contour maps of pre-multiplied spectra for the streamwise component of the velocity fluctuation in a zero pressure gradient turbulent boundary layer.

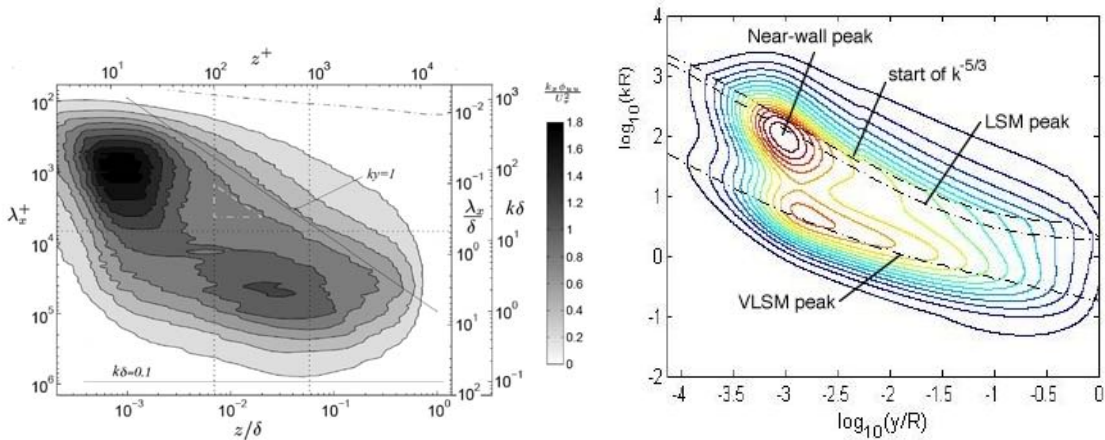


Figure 3: Contour maps of pre-multiplied spectra for the streamwise component of the velocity fluctuation in a zero pressure gradient turbulent boundary layer for  $Re_\tau = 14000$ . Left: data from Hutchins & Marusic (2007b); right: model predictions.

During the course of the project it was realized that the model could also form the basis of a correction scheme for hot-wires with unresolved energy due to limited spatial resolution. This is a particularly common problem in high Reynolds number measurements where the viscous length can be very small (significantly smaller than most hot-wires). Some preliminary results for the correction scheme are shown in Figure 4. The corrected profiles are found to have excellent agreement. This aspect of the research is ongoing and a manuscript is in preparation.

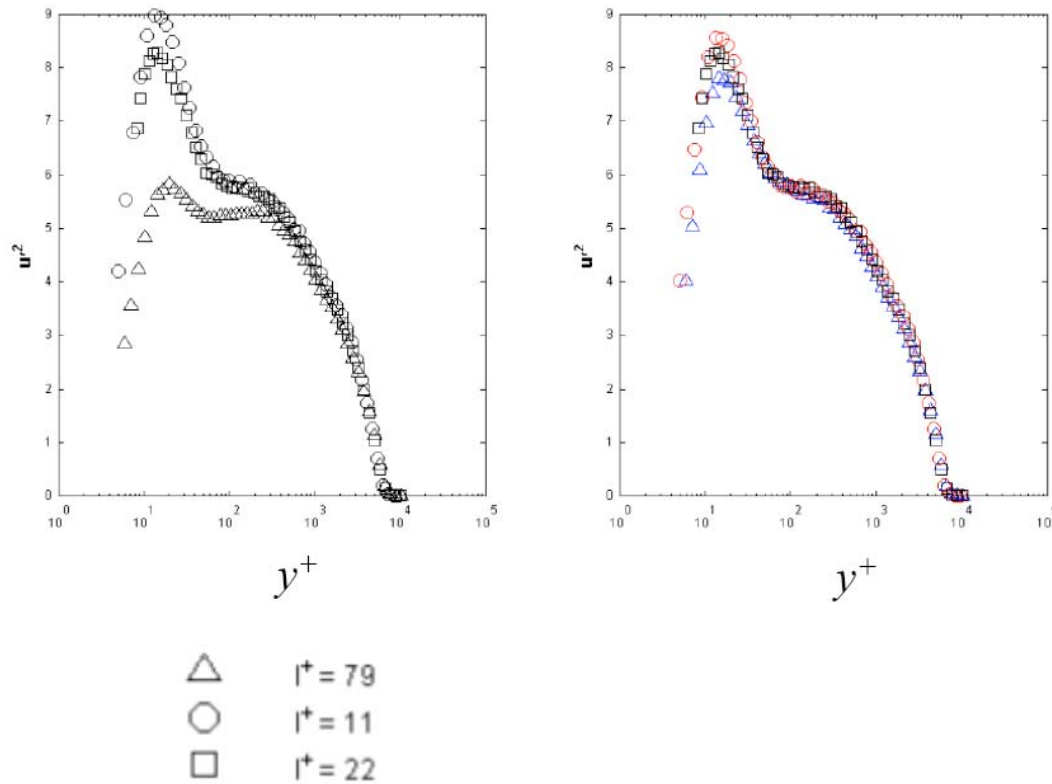


Figure 4. Left hand plot shows turbulence intensity profiles in the HRNBLWT at  $Re_\tau=7300$ , using three different hot-wires with varying sensing lengths ( $l^+=11,22,79$ ). The attenuation due to the effects of spatial are clearly noted. Right hand plot shows data corrected using the model.

The final aspects of the research relates to the very high Reynolds number flows associated with the Utah salt-flats. This database was interrogated and emphasis was placed on understanding the effect of buoyancy on the structure angle and other turbulence statistics. This information is vital in heated wall applications. This aspect of the work was submitted to the USNCTAM2010 meeting (16th US National Congress of Theoretical and Applied Mechanics, to be held June 27-July 2, 2010, State College, Pennsylvania, USA) and we plan on reporting our results there. The main finding is an empirical correlation between the structure angle (important for near-wall models in large-eddy simulation) and the Monin-Obukov length (a dimensionless measure of buoyancy).

## 6. Personnel Supported

The funding directly supported in part two doctoral researchers: Dr. Kapil Chauhan and Dr. Romain Mathis. Other academics who directly contributed to aspects of the research



program include Dr. Nicholas Hutchins, Mr. Cheng Chin (PhD candidate) and Dr. Jason Monty.

## **7. Publications**

Marusic I, Mathis R, & Hutchins N. (2010). High Reynolds number effects in wall turbulence. *Int. J. Heat Fluid Flow. In press*

Chauhan K, Marusic, I, Hutchins, N., Monty, J. & Chong M.S. (2010) Structure of coherence in neutral and thermally buoyant atmospheric surface layers. *Proceedings of USNCTAM201: 16th US National Congress of Theoretical and Applied Mechanics June 27-July 2, 2010, State College, Pennsylvania, USA (Under review)*

## **8. Interactions**

We have had extensive interactions with Professor A.J. Smits of Princeton University and his group. We also were visited by Professor Pino Martin, from the University of Maryland, from December 1-6, 2009 on a trip funded by AFOSR. We discussed how we could use our theoretical model to develop near-wall models for LES. This collaboration is ongoing and promising. We are planning to send one of our new graduate students to the University of Maryland for a visit to further this work.

## **9. Inventions**

None

## **10. Honors/Awards**

None

## **11. Archival Documentation**

None

## **12. Software and/or Hardware**

None

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